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High-Efficiency Class E RF Generators using GaN FETs

A novel circuit topology has been developed for applications requiring high-voltage RF energy. It uses an unusual combination of an RC-based oscillator, a GaN FET and driver to deliver RF power at efficiencies over 95%.

By Tolga Aydemir, principal electronics consultant at 42 Technology

Advances in radio frequency (RF) generation have led to innovative designs transforming applications within the sub-100 MHz region. Among these, high-efficiency self-oscillating Class E RF generators stand out for their simplicity, robustness, and remarkable performance by leveraging Gallium Nitride (GaN) transistors. These generators can achieve efficiencies over 95% with output voltages of several kV from a few watts up to 1 kW depending on the application.

Self-oscillating Class E generators are ideal for generating high-voltage RF signals efficiently in applications where precise oscillation frequency is less critical, as they eliminate the need for external signal sources or strict frequency controls. Self-oscillating designs also benefit from automatically tuning to minor variations in resonant tank circuit parameters, making them resilient to component tolerances and environmental variations. By implementing self-oscillation in a GaN-enabled Class E driver stage, along with GaN drivers, this design further enhances efficiency due to the superior switching characteristics of GaN devices. Additionally, a kick-start circuit increases reliability by ensuring the oscillation initiates correctly upon power-up.

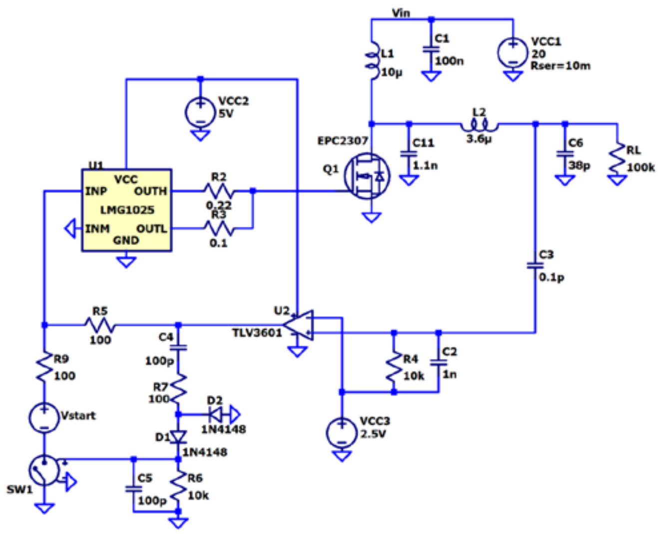

Figure 1: Self-oscillating Class E generator operating at 13.56 MHz.

Design and operation

Figure 1 shows a self-oscillating Class E generator operating at 13.56 MHz. This design leverages GaN FETs to achieve over 95% efficiency while generating output voltages of several kV, making it suitable for use in applications such as dielectric heating, ion traps, and RF lasers used within industrial, scientific research and medical sectors.

Initial start-up and oscillation

When the circuit is first powered on, Vstart provides the initial signal to kick-start the oscillation process. Vstart is an oscillator running at a frequency close to the intended operating frequency of the Class E stage (13.56 MHz). Its output is coupled through resistor R9 into the input of the gate driver U1 (LMG1025).

The gate driver drives the gate of Q1 (EPC2307 GaN FET), causing it to start switching at the Vstart frequency. As Q1 switches on and off, it drives the resonant tank circuit formed by L2 and C6. C11 acts as the shunt capacitor typical in a Class E configuration, shaping the voltage waveform. The tank circuit builds up energy, and the AC voltage amplitude at the node connecting L2, C6, RL, and C3 increases, producing an almost sinusoidal waveform.

Feedback and self-oscillation mechanism

The AC signal from the tank circuit is picked up by capacitor C3 and fed into the positive input of the comparator U2 (TLV3601). Resistor R4 and capacitor C2 form a voltage divider and provide a DC bias. The negative input of the comparator is connected to a DC reference voltage (VCC3).

When the AC amplitude is sufficient, U2 toggles its output in phase with the AC signal, following the initial Vstart frequency. The comparator's output charges the peak detector circuit composed of C4, R7, D1, D2, R6, and C5. Once the voltage across C5 reaches a threshold (e.g., 1 V), it triggers SW1 to stop the Vstart signal, allowing the circuit to enter self-oscillation mode.

Self-oscillation and steady-state operation

In self-oscillation mode, U2 continues to drive U1 using feedback from the resonant tank circuit. The self-oscillation frequency is determined primarily by L2 and C6, settling at approximately 13.56 MHz in this particular design. The circuit is carefully tuned to stay within the Class E operating region, ensuring high efficiency by minimising the overlap between voltage and current during Q1's switching.

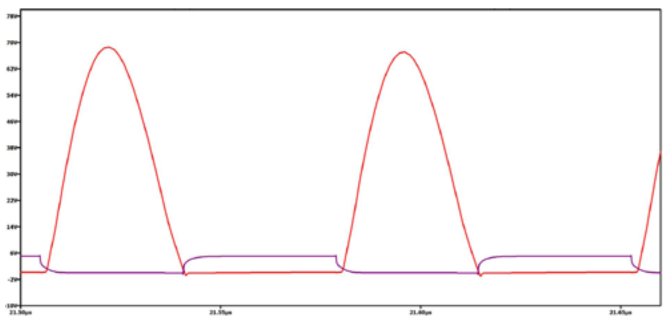

Figure 2: Drain and gate voltage waveforms confirm Class E operation.

Performance insights

Figures 2 and 3 provide further insights. Figure 2 shows the drain and gate voltage waveforms of the GaN FET, confirming Class E operation as the FET switches on when the drain voltage reaches zero, minimising power dissipation during transitions. Figure 3 illustrates the amplitude build-up on the load after powering the circuit, demonstrating efficient energy transfer and rapid attainment of steady-state oscillations.

Output voltage and efficiency

At the optimal operating point, the output voltage across RL is approximately 2.75 kV RMS, with a power dissipation of 75.5 W on RL. The simulated efficiency is over 95%. However, the measured efficiency in practical implementations tends to be slightly lower because of factors such as component imperfections, parasitic elements and additional circuit losses not accounted for in the simulation. With further tuning and optimisation, this circuit can be adapted for dielectric heating, ion traps or RF laser applications.

Managing component drift and load variations

The high-Q resonant tank circuit is sensitive to minor variations in components L2 and C6, affecting output amplitude and efficiency; and load deviations from the target (e.g., 100 kΩ) can also lead to reduced efficiency and potential overheating of the GaN FET.

Auto-tuning techniques, such as using voltage-controlled tunable capacitance in the shunt and tank capacitors via MOSFETs, are able to address these issues. Adaptive control mechanisms can adjust circuit parameters in real-time to help maintain optimal performance despite component drift or load changes.

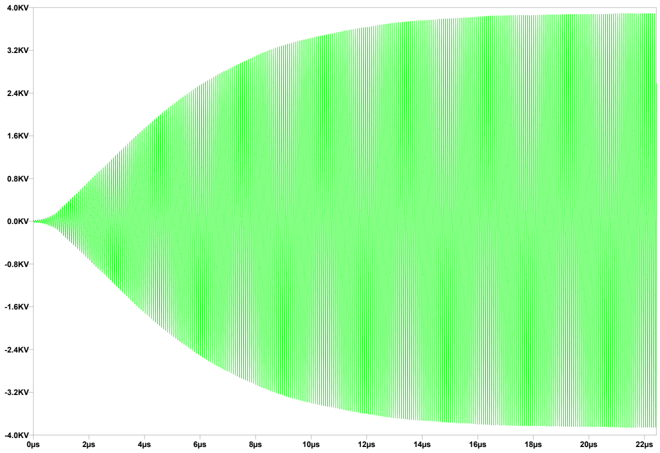

Figure 3: Amplitude build up on the load after powering the circuit.

Transforming industries with RF power

Innovations in self-oscillating Class E RF generators are part of a broader trend impacting various fields within the sub-100 MHz region. For example, RF energy powers dielectric heating for drying and curing plastics and for cooking food, and to power RF lasers (e.g, CO_2) for precision cutting, welding and engraving. Semiconductor fabrication uses RF-powered plasma to etch and deposit materials at micro and nano scales. RF systems are also indispensable in particle accelerators, mass spectrometry ion traps, and in medical treatments such as RF ablation to destroy cancerous cells or to correct heart arrhythmias through minimally-invasive procedures.

Solid-state RF and non-linear efficiency

The transition from vacuum tube-based systems to solid-state technology has revolutionised RF generation. GaN FETs offer increased efficiency, reduced heat, and smaller, more reliable designs. Solid-state systems also extend lifespans and lower operational costs, and with recent advances now enabling them to handle power levels previously managed only by tube-based systems. Operating active devices as switches leads to higher efficiency but lower linearity, which is an acceptable trade-off in many RF applications where precise linear amplification is not required.

Class E generators can achieve efficiencies of between 85% and 95% and offer simple designs, making them well-suited for RF heating and plasma generation. Class F generators can theoretically exceed 90% efficiency and are suitable for high-power output at RF frequencies where linearity is less critical. Class D half-bridge generators are frequently used at frequencies like 13.56 MHz in industrial RF heating and plasma generation but become less efficient at higher frequencies due to increased switching losses.

Conclusion

The development of high-efficiency self-oscillating Class E RF generators is transforming applications within the sub-100 MHz region. By harnessing the advantages of GaN technology and innovative design approaches, these generators can deliver exceptional performance. Their ability to generate high-voltage RF energy efficiently and reliably will help to open up significant new possibilities, as well as boosting existing technologies across multiple sectors.

Before implementing these systems, readers are advised to consult detailed engineering texts and technical resources to address any specific design challenges and safety considerations.

About the Author

Tolga Aydemir is principal electronics consultant at 42 Technology, a product design and innovation consultancy based near Cambridge, UK. He has spent over 25 years in product development companies and research centres, and has significant experience in designing analogue electronics, power systems and embedded systems. Tolga is particularly focused on power electronics and analogue sensor interface development, and holds several patents in electricity metering and light control sectors.

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